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Using discrete element models to track movement of coarse aggregates during compaction of asphalt mixture

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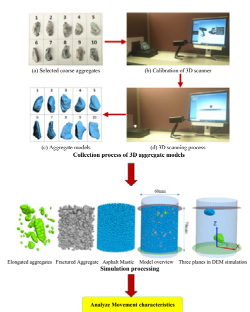
HIGHLIGHTS

- Analyzed and simulated movement characteristics of aggregates with DEM.
- Three main stages of particle movement were identified in the SGC test.
- Displacement and rotation of aggregates were captured and analyzed.
- Rounded, elongated, & flat shapes of aggregates affect displacement and rotation.

GRAPHICAL ABSTRACT



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ABSTRACT

The objective of this study is to analyze the movement characteristic of differently-shaped compositions in the Superpave Gyratory Compactor (SGC) test through tracking coarse aggregates and the numerical simulation of Discrete Element Method (DEM). First, the coarse aggregates were classified into five shape types (rounded, fractured, angular, elongated and flat) and scanned by a 3D scanner. Second, seven groups of asphalt mixtures with different combination types of hybrid, 100%fractured, 100%angular, 80%fractured + 20%rounded, 60%fractured + 40%rounded, 80%fractured + 20%elongated, and 80%fractured + 20%flat groups were simulated by Particle Flow Code (PFC) Version 5. Third, numerical simulations were conducted to analyze the SGC test process and the movement paths of differently-shaped coarse aggregates were obtained. Finally, statistical analysis on the results from the modeling test were used to study the movement characteristics of asphalt mixtures with differently-shaped aggregate compositions. Through this study, it was found that: (1) there were three main stages of particle movement in the SGC test; (2) the ratio of vertical displacement was obviously larger than that of horizontal displacement, while the variation of vertical rotation was obviously smaller than that of horizontal rotation in asphalt mixtures with differently-shaped compositions; (3) the rounded, elongated and flat coarse aggregates have greater influence on horizontal displacement compared with vertical displacement, but have adverse effects on particle rotations during the compaction process; (4) the effects of elongated coarse aggregates on particle movement were larger than those of flat coarse aggregates, but the flat coarse aggregates have more influence on particle rotation for the variations of horizontal and vertical rotational angles.

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1. Introduction

Aggregates account for 95% of asphalt mixture by weight and the morphological features play a crucial part in the performance of asphalt mixtures [1,2]. In particular, the shapes of aggregates have effects on the compaction performance of asphalt mixtures [3–6]. In order to study the influence of aggregate shapes on asphalt mixture compaction, a large number of experiments have been conducted.

For describing and analyzing the shapes of aggregates, image processes, computer programs, mathematical methods, fractals and statistical approaches were utilized [7–12]; 2D or 3D images of aggregate particles were obtained by camera, scanner or X-ray computed tomography (CT) to rebuild the models for analyzing morphological features [13–15]. In addition, lots of researchers have aimed to study the parameters and characteristics of compaction by the following laboratory or file methods: the effects of different gradation types, temperatures, pressures and procedures on the asphalt mixture compaction were revealed through the Marshall and Superpave Gyratory Compaction (SGC) test [16–18]; contrastive studies have been carried out to evaluate the volumetric and mechanical performances of asphalt mixture [19]; the relationship between the aggregate geometrical features and the asphalt mixture formation process and performances were investigated [20]; and the densification curve of the SGC test was utilized to study the effects of material composition such as the proportion of mineral aggregates, asphalt content and other additional agents on compaction characteristics of asphalt mixtures [21]. Recently, one popular numerical simulation, the Discrete Element Method (DEM), was employed into civil engineering for mix performance analysis [22–25]: in some studies, the aggregates were simulated based on the regular shapes in the user-defined models for mixtures [26,27]; the dynamic modulus was simulated and analyzed by DEM and X-ray CT images [28]; numerical method was applied to record the movement of coarse aggregates in the compacting process of asphalt through the 2D digital images [29]; in order to explain the compaction mechanism during SGC test, the SmartRock sensors were used to monitor detect the characteristic of particle movement [30].

The objective of this study is to investigate the movement characteristics in the SGC test through tracking differently-shaped coarse aggregate particles and numerical simulation. The main work includes: (1) classifying and selecting the coarse aggregates into five differently-shaped types; (2) 3D scanning and rebuilding aggregate models; (3) preparing seven groups of compacted samples with different combinations of differently-shaped coarse aggregates; (4) building discrete element models and simulating the compacting process of mixture to track the movement of coarse aggregate; and (5) analyzing the results from DEM simulation to obtain the movement characteristics of differently-shaped types.

2. Classification and 3d scanning of coarse aggregates

2.1. Classification of coarse aggregates

In this study, as aggregates are one of the most important materials of asphalt mixtures, the first step is to classify and select different shapes of aggregates. According to the ASTM D 4791 and 5821 [31,32], the coarse mineral aggregates from Eagle River were divided into five different types shown in Fig. 1: Type I rounded (T1), Type II fractured (T2), Type III angular (T3), Type IV elongated (T4) and Type V flat (T5). The properties of aggregates were shown in Table 1.

2.2. 3D scanning of coarse aggregates

A Wiiboox 3D scanner with 0.1 mm resolution was used to obtain the 3D information and rebuild the 3D models of the different shapes of coarse aggregates. As shown in Fig. 2(a)–(d), the scanning processes are divided into four steps:

- Before 3D scanning all selected shapes (T1-T5) were numbered from 1 to 10 (indicating 10 subtypes for each type) and sprayed with a specific developer to obtain optimized features of the aggregates shown in Fig. 2(a).
- To ensure the reliability and repeatability of the scanning results, the equipment was set up and calibrated shown in Fig. 2(b).
- The colored coarse aggregates were placed on the automatic turntable and a 3D scan was conducted shown in Fig. 2(c).
- 3D scanning data of coarse aggregates was collected and stored in STL (stereolithography) files shown in Fig. 2(d).

3. Discrete element simulation of compaction test

3.1. Configuration of models with differently-shaped aggregates

The gradation of the mixture is shown in Table 2 and the optimum asphalt content of 5.5% by weight of mix was used during the numerical simulation procedure of the SGC test. Coarse aggregates 4.75 mm or larger than were replaced by specific combinations of

Table 1
Properties of aggregates.

Properties	Test Value	Standard
L.A.abrasion (max), % loss (c)	15	MTM 102
Angularity Index (Min)	43.0	MTM 118
Aggregate Wear Index Factor	1.0	MTU 111 &112
Aggregate Wear Index Value #16	339	MTM 112
Soft Particles (% Max)	0.50	MTM 110
Flat and Elongated (% Max)	0.90	ASTM D 4791

Fig. 1. Five types of coarse aggregates.